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# *Engineering Reliability Analysis for Prioritizing Investment Decisions*

David M. Schaaf, P.E.
USACE Regional Technical Specialist, Louisville District

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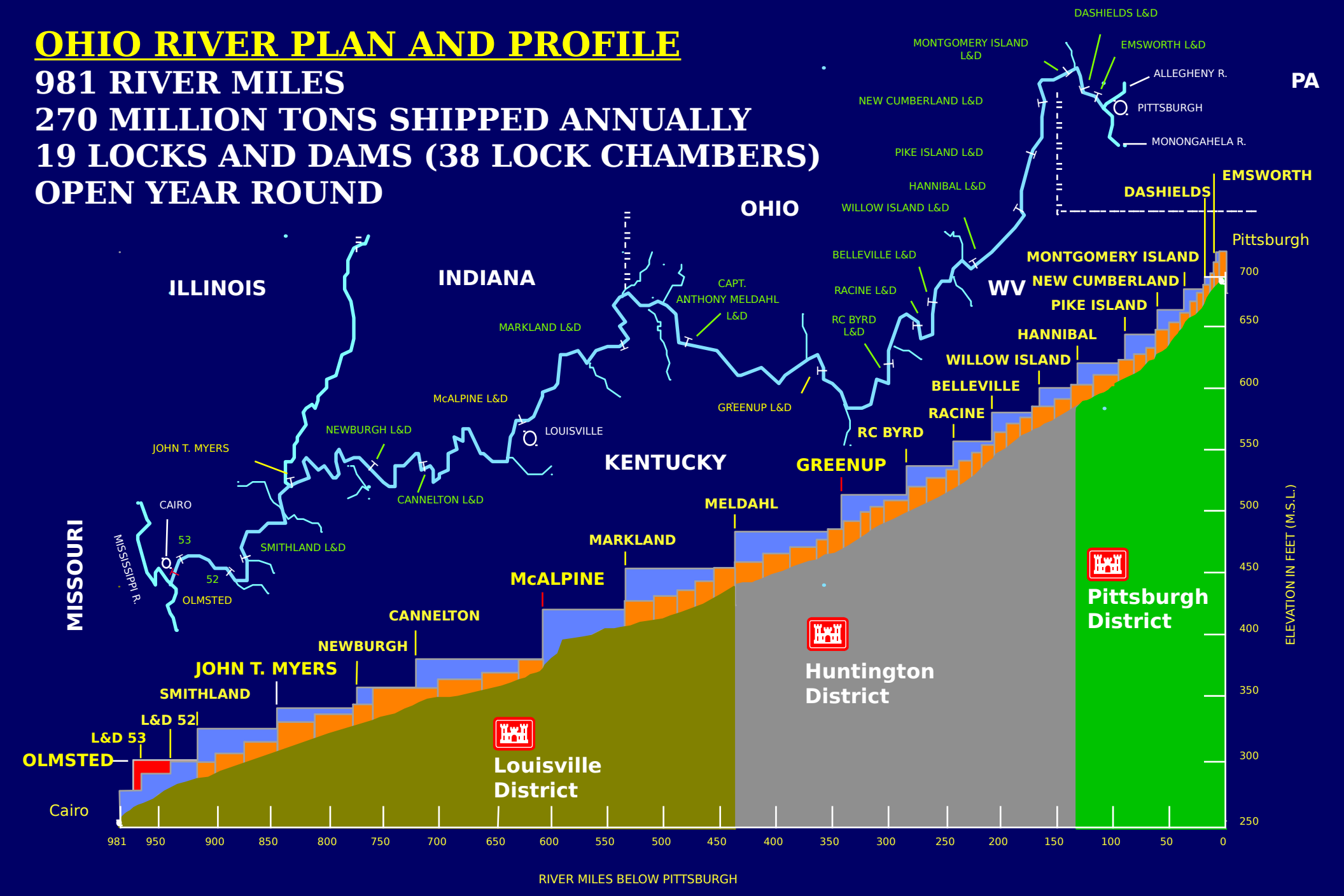
# Outline of Presentation

- Existing System of Ohio River Locks and Dams
- Ohio River Mainstem Systems Study
  - *Engineering Reliability Features*
  - *Integration with Economics*
- Ohio River Navigation Investment Model
  - *Capabilities and Uses*
- Future and On-Going Studies
  - *Great Lakes/St. Lawrence Seaway & Panama Canal*

# OHIO RIVER PLAN AND PROFILE

**981 RIVER MILES**
**270 MILLION TONS SHIPPED ANNUALLY**
**19 LOCKS AND DAMS (38 LOCK CHAMBERS)**
**OPEN YEAR ROUND**



# Markland Locks and Dam (Typical Configuration)

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# Ohio River Project Details

| Project | District | Year Built | Annual Tonnage | Annual Recreational Vessels | Annual Number Tows |
|---|---|---|---|---|---|
| Emsworth | LRP | 1921 | 23,000,000 | 5,300 | 4,000 |
| N.Cumberland | LRP | 1959 | 37,000,000 | 4,600 | 1,800 |
| Hannibal | LRP | 1972 | 46,000,000 | 4,300 | 900 |
| Willow Island | LRH | 1972 | 44,000,000 | 3,800 | 1,600 |
| RC Byrd | LRH | 1993 | 59,000,000 | 5,400 | 700 |
| Greenup | LRH | 1959 | 70,000,000 | 6,400 | 700 |
| Markland | LRL | 1959 | 55,000,000 | 5,200 | 4,100 |
| John T. Myers | LRL | 1975 | 72,000,000 | 6,600 | 2,500 |
| Olmsted* | LRL | 2014 | 94,000,000 | 9,900 | 1,700 |

(* Current Level)

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# Ohio River Mainstem Systems Study

## Assessing the Condition of All Project Features

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# Engineering Reliability Analysis

## What is it? Why is it used? What is the Justification for its Use?

- Required by USACE Guidance for Specific Types of Investments
  - Major Rehabilitation Projects (Markland, Emsworth, J.T. Myers)
  - New Project Authorization Based Upon Deteriorated Condition of Existing Project (Chickamauga)
  - Systems Studies Recommendations (ORMSS and GLSLS)
- Recognizes and Captures Uncertainty in Engineering and Economic Analyses
  - Engineering Uncertainties – Loads, Material Properties, Corrosion, Fatigue
  - Economic Uncertainties – Traffic Forecasts, Rate Savings
- Shows Economic Justification and Risks Associated with Multiple Future Investment Alternatives
  - Fix-as-Fails Maintenance, Advance Maintenance, Major Rehab
- Allows an Unbiased Method to Rank Projects Based Upon Risks and Economic Merit

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# *Ohio River Mainstem Systems Study*

## Forecasting the Future

- Traffic Forecasts
- Lock Capacity
- Lock Reliability
  - Structural condition of lock and dam components
  - Cost of repairing lock components compared to replacing components ahead of failure
  - Operational effect of lock repairs (do they cause significant impacts to navigation, pool levels, and/or  other impacts)

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# *Ohio River Mainstem Systems Study*

## Introduction to Systematic Evaluation

- Investment Plan for Ohio River Navigation System for 2005 - 2065
- Multi-Project, Multi-District, Multi-Discipline
  - Pittsburgh, Huntington, and Louisville Districts
  - Engineering, Economics, Plan Formulation, and Environmental
- Prioritization Among Maintenance, Rehabs, New Construction for All 19 Projects
  - Projects ages vary from 80+ years to under construction
  - Traffic levels and lock chamber dimensions vary
- Reliability Had Significant Impact on Economic Analysis and was used to Time Improvements

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# ORMSS
## Engineering Reliability Integration

- Aging System of Locks and Dams
  - Most projects approaching original design life of 50 years
  - Most projects will be near 100 years old by end of study
- Older, Deteriorated Projects Need Condition Upgrades
- High Traffic Projects Need Capacity Enhancements
- Reliability Used to Justify and Time Project Upgrades
- Most Critical System Components Analyzed
  - Excessive repair cost and/or excessive down time
- Bottom Line – Where is Best Place to Put Limited Funds???

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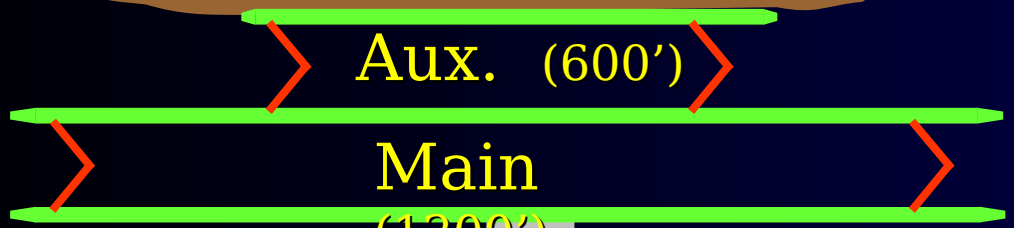
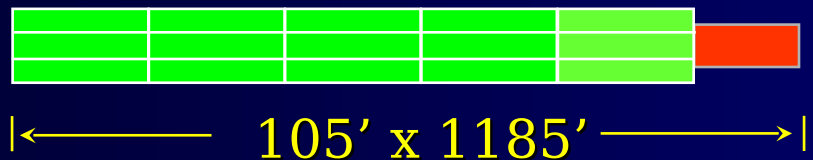
# Typical Ohio River Main & Auxiliary Locks

When both chambers open
transit thru
facility usually takes 1 hour +/-




Typical 15 Barge Tow

## Lock Chamber Closures

Maintenance (Scheduled)
Inspections (Scheduled)
Component Failures (Unscheduled)
Accidents (Unscheduled)
Emergency Repairs (Unscheduled)

**** Need predictive tools to make wise decisions and maximize life of components**

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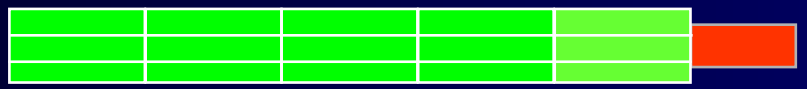
# Typical Ohio River
# Use of Auxiliary Locks

Main chamber closed, transit time g
increased due to short auxiliary cha



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# Typical Ohio River
# Use of Auxiliary Locks

Tow has to “double-cut” to process th
facility. Queue begins to build.

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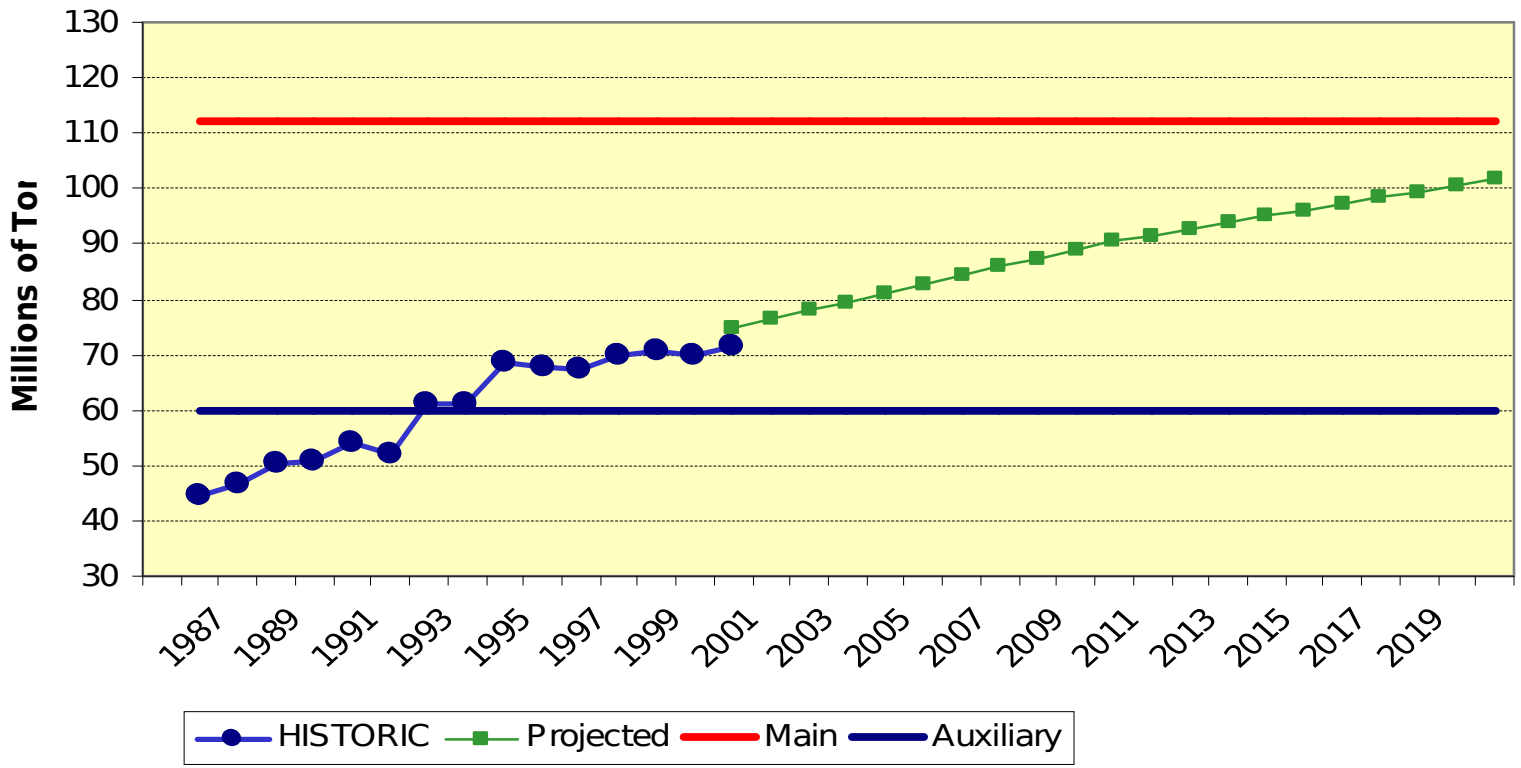
# Assessment of Needs

## Capacity & Traffic



# McAlpine 1999 Main Chamber Dewatering

Tows Waiting to Lock Through
Short, Inefficient Auxiliary Chamber

# Economic Impacts of Main Closures

| Event | Duration | Delay $ | Repair $ | Total $ | Peak Delay |
|---|---|---|---|---|---|
| McAlpine* April 2005 | 2 days | 1.0 M | Reimbursed by Barge Co | 1.0 M | 75 hours (3 days) |
| Greenup** Oct. 2003 | 52 days | 13.2 M | 1.5 M | 14.8 M | 93 hours (4 days) |
| Markland June 2005 | 13 days | 0.6 M | 0.8 M | 1.4 M | 33 hours |
| McAlpine Sept. 1999 | 15 days | 3.1 M | 0.8 M | 3.9 M | 86 hours (3 ½ days) |

*** McAlpine was unscheduled closure due to a barge impacting a cofferdam at the site. The lock had to be closed for 2 days while emergency repairs were made.**

**** Greenup was partially scheduled. Originally scheduled for 21 days, gate condition required 52 days to make extensive repairs. Additional $30 million in costs to end users also identified.**

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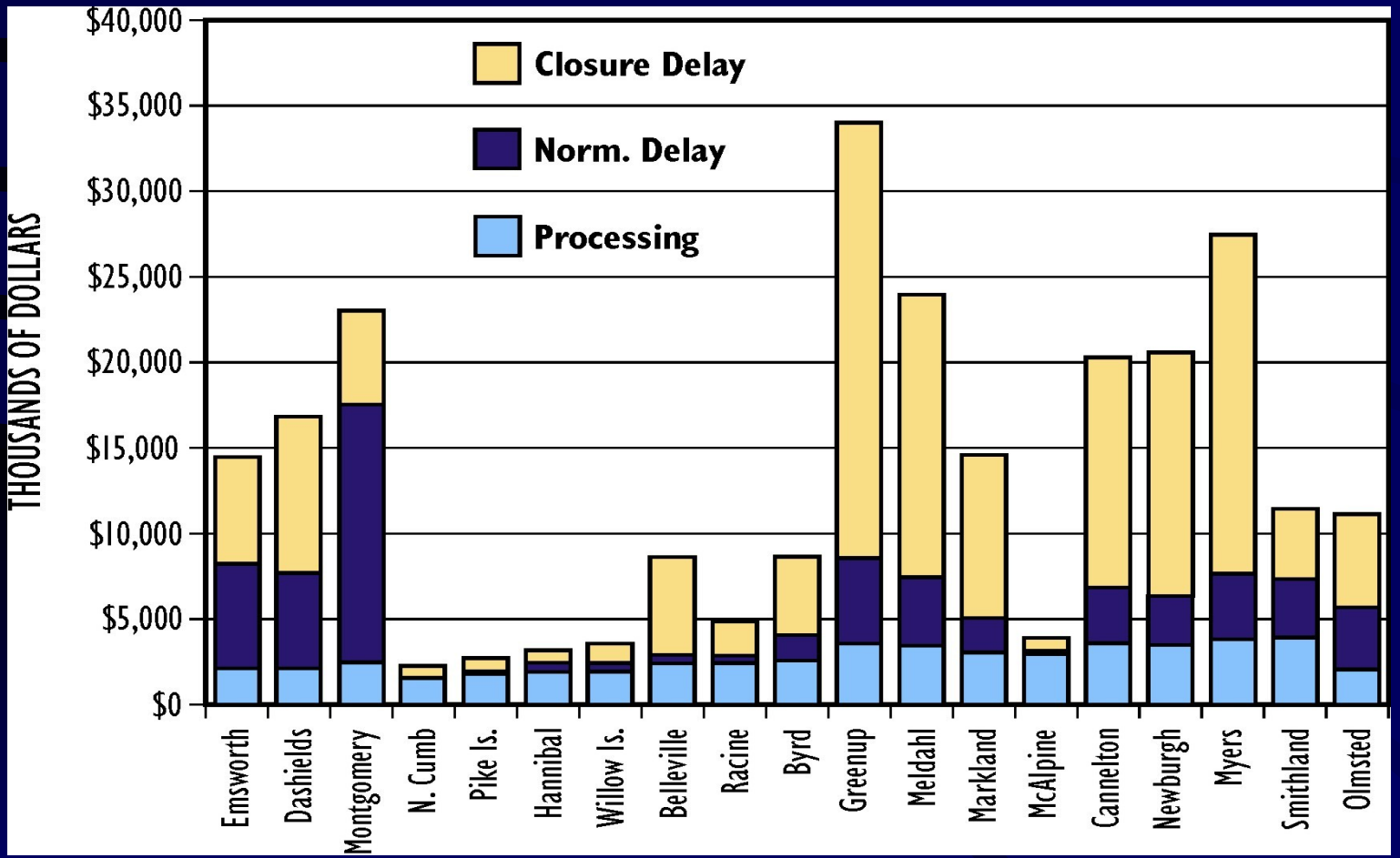
# ORMSS Economic Impact

## Average Annual Transit Costs by Category

### FUTURE CONDITION W/O LARGE-SCALE IMPROVEMENTS



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# ORMSS Reliability Integration

## Selection of Critical Components

- Two Phase Screening Process Used to Select Components
  - Site Inspections, Interviews, Review of Plans Led to Global List of 170 Components
  - Phase 1 Screening Eliminated Components of Low Consequence (60 Survived)
  - Phase 2 Screening Used a Numerical Rating System (15 Survived)
- 15 Components Required Reliability Modeling
  - Non-Time Dependent Components
  - Time Dependent Components

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# *ORMSS Reliability Integration*

## Types of Components

- **Non-Time Dependent Components**
  - Typically Gravity Structures That Do Not Change With Time
  - Analyzed for Multiple Failure Modes
  - Multiple Load Cases
  - Reliability Model Produces PUP's That Remain Constant

- **Time Dependent Components**
  - Structures That Degrade Over Time
  - Example - Steel Structures Subject to Corrosion and Fatigue
  - Reliability Model Produces Hazard Functions

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# ORMSS Reliability Integration

## Non-Time Dependent Components

**STABILITY ANALYSIS OF UNANCHORED GRAVITY STRUCTURES**

- Land, River, Middle Wall Monoliths
- Guide and Guard Wall Monoliths
- Miter Gate Monoliths
- Miter Gate Sills

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# *ORMSS Reliability Integration*

## Non-Time Dependent Components

**LOAD CASES**

Normal Operating
Maintenance Dewatering

**LIMIT STATES**

Sliding at the Base
Deep-Seated Sliding
Overturning
Bearing Capacity

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# ORMSS Reliability Integration

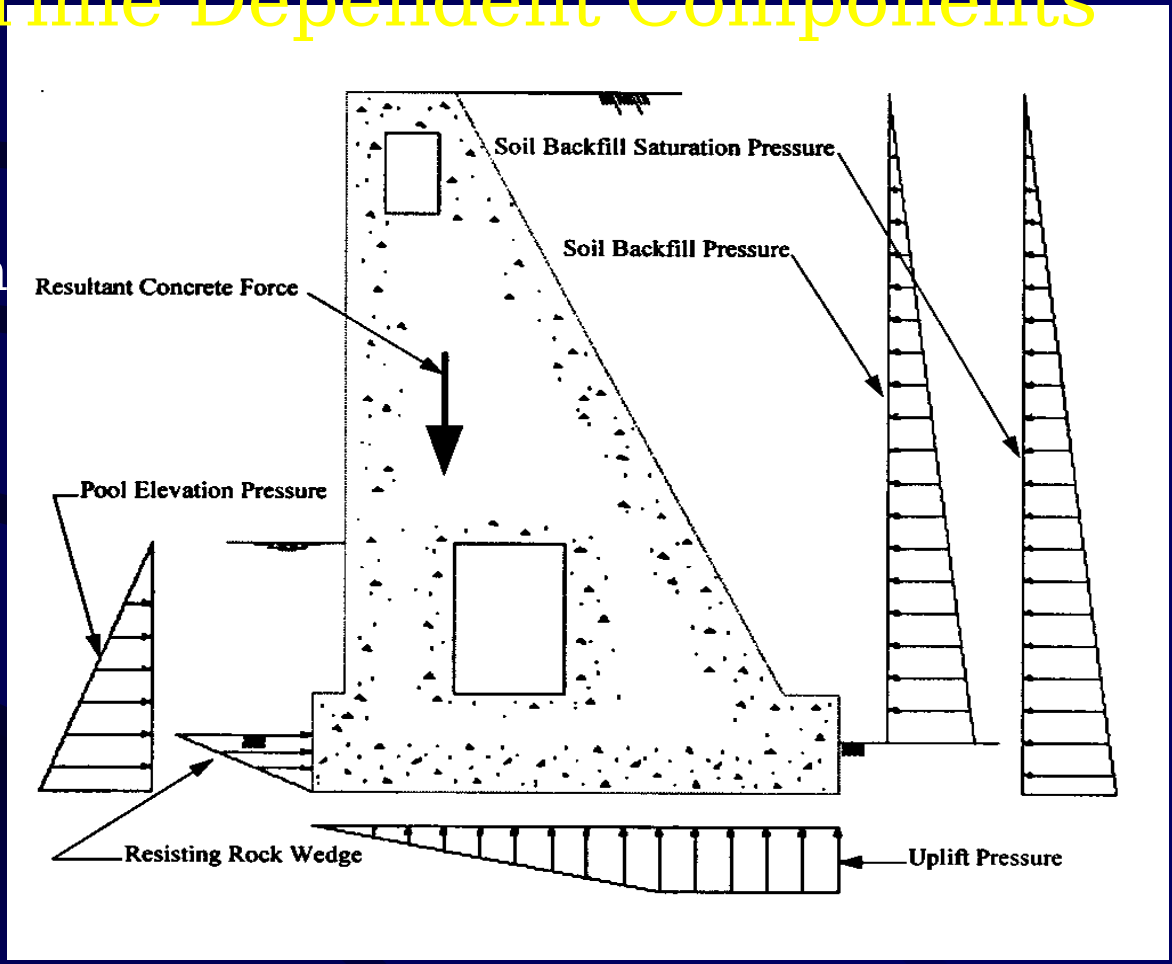
## Non-Time Dependent Components

**Random Variables**

- Lower Pool Elevation
- Soil Unit Weights and Strength
- Soil Backfill Saturation Level
- Rock Strengths
- Barge Impact Force
- Hawser Force

**Constants in Analysis**

- Upper Pool Elevation
- Concrete Unit Weight
- Water Unit Weight



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# ORMSS Reliability Integration

## Non-Time Dependent Model Details

- **10,000 Iterations for Normal Load Case**
  - Monte Carlo Simulation of Random Variables Used
  - @Risk™ Software Used for Simulation
  - Spread Sheets Used for Computations
  - Analysis Produces Single PUP for Normal Load Case
- **10,000 Iterations for Maintenance Case**
  - Lock Chamber Dewatered Every 5 Years On Average
  - Typically Represents Worst Load Case for Lock Wall Stability
  - Analysis Produces Single PUP for Maintenance Load Case
- **Event Tree Formatted for Both Load Cases**

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# ORMSS Reliability Integration

## Time Dependent Components

### STRUCTURAL MODELS

HF Miter Gates
VF Miter Gates
Anchored Monoliths
Anchored Sills
HF Culvert Valves
VF Culvert Valves

### MECHANICAL/ELECTRICAL

MG Machinery
CV Machinery
Lock Hydraulic
Lock Electrical

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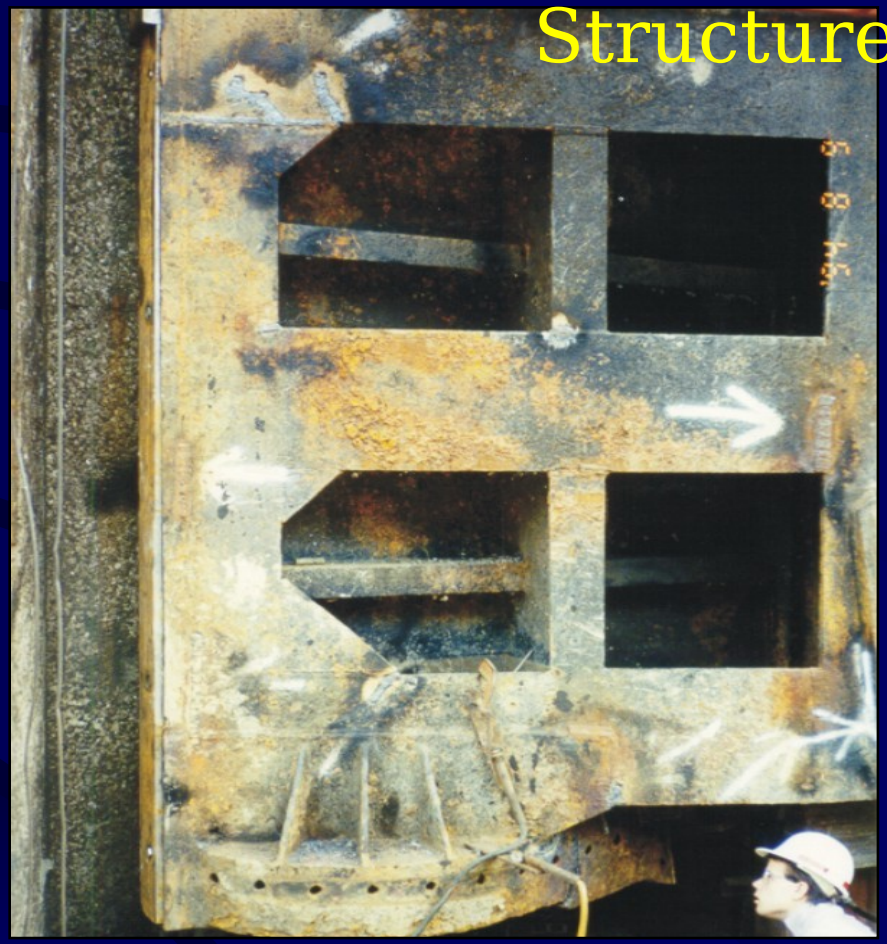
# ORMSS Reliability Integration

## Establish the Current Condition of Structure

CULVERT VALVE FAILURES

MITER GATE FAILURES



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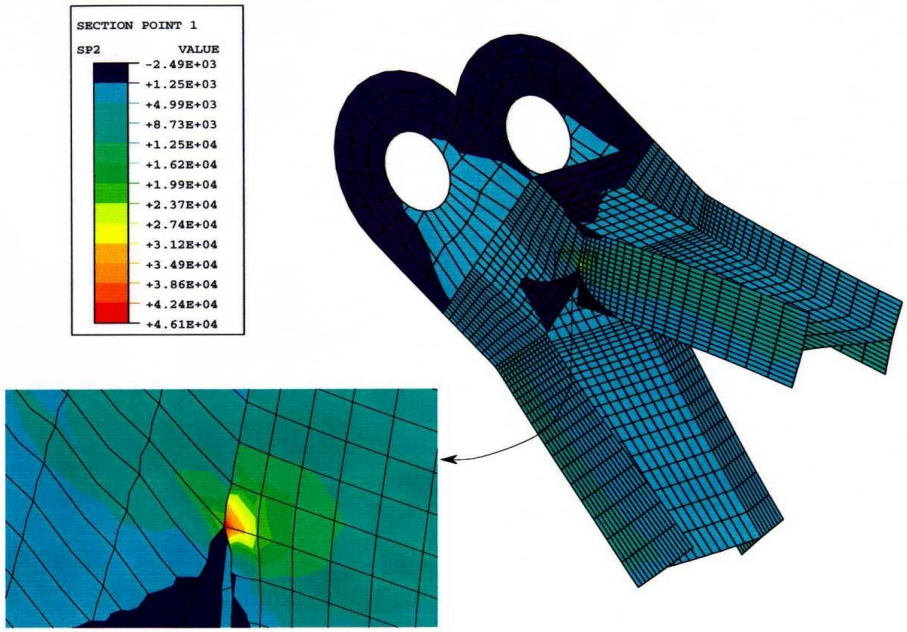
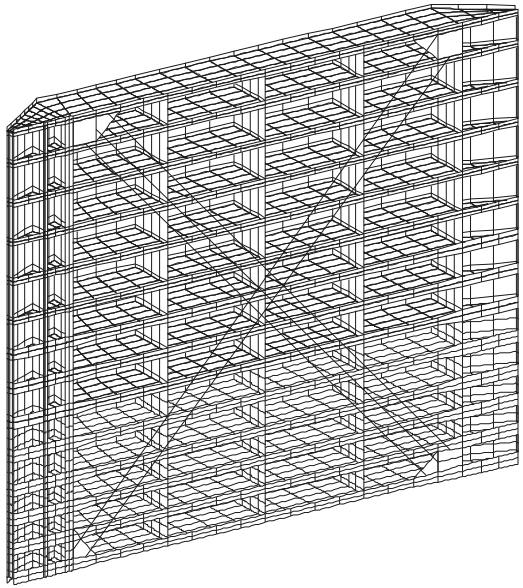
# ORMSS Reliability Integration

## Advanced Modeling for Realistic Failure Modes

### LOCAL F.E. MODELING

- Establishes Residual Stress Distribution
- Crack Initiation and Propagation
- Benchmark with Field Cracking/Measurements



### GLOBAL F.E. MODELING

- Load Distribution on Global Structure
- Stress Distribution for Varying Ops
- Determination of Areas of High Stress

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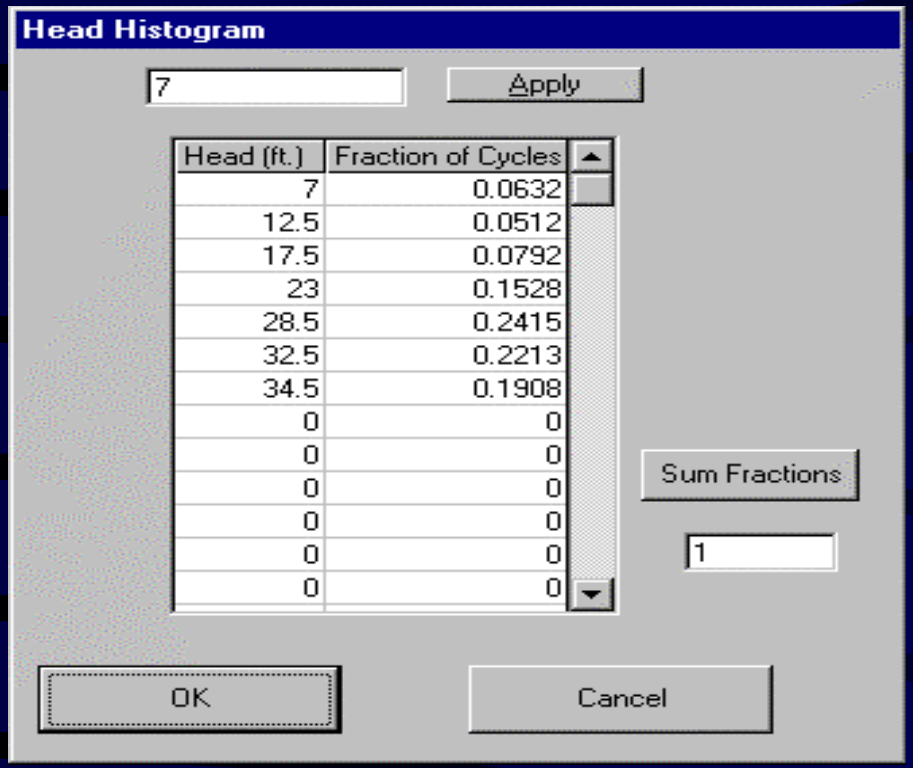
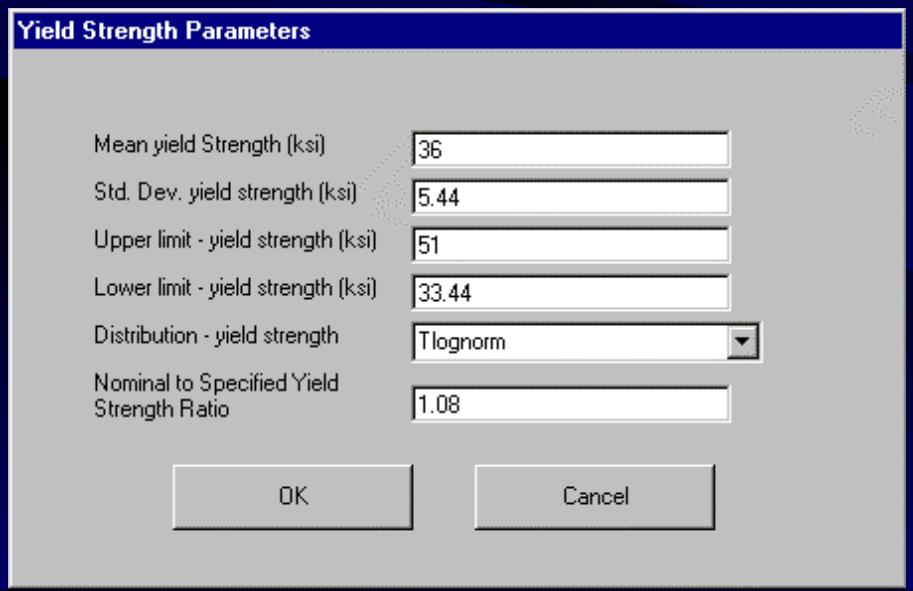
# *Time Dependent Reliability Modeling*

## Summary of Model Features

- Miter Gate and Culvert Valve Reliability
  - F.E. Modeling Used as Basis for Reliability Model Input
  - Calibration and Limit State Developed Using F.E. Modeling
  - Custom Coded Reliability Model Developed in Visual Basic
  - Monte Carlo Simulation (Speed Allowed 50,000 Iterations)

- Mechanical and Electrical Models Were Developed using Failure Rates from Established Publications Within MS Excel Spreadsheet





Yield Strength Parameters
Mean yield Strength (ksi) 36
Std. Dev. yield strength (ksi) 5.44
Upper limit - yield strength (ksi) 51
Lower limit - yield strength (ksi) 33.44
Distribution - yield strength Tlognorm
Nominal to Specified Yield Strength Ratio 1.08
OK
Cancel

# Example HWELD Input Menus

- Miter Gate Properties
  - Girder Spacing, Length
  - Skin Plate Properties
- Girder/stiffener properties
  - Flange, Web Thickness
- Operating Cycles
  - Historic and Projected
- Yield Strength of Steel (Random)
- Corrosion Parameters (Random)
- Stress Concentration Factors (Random)
  - Determined from F.E. Modeling
- Pintle Wear / Misalignment Factor (Rand
  - Determined from F.E. Modeling
- Head Histogram (Acts Random)
  - Determined from LPMS Data
- Maintenance Strategy
  - Fix-As-Fails, Adv. Maintenance, etc.

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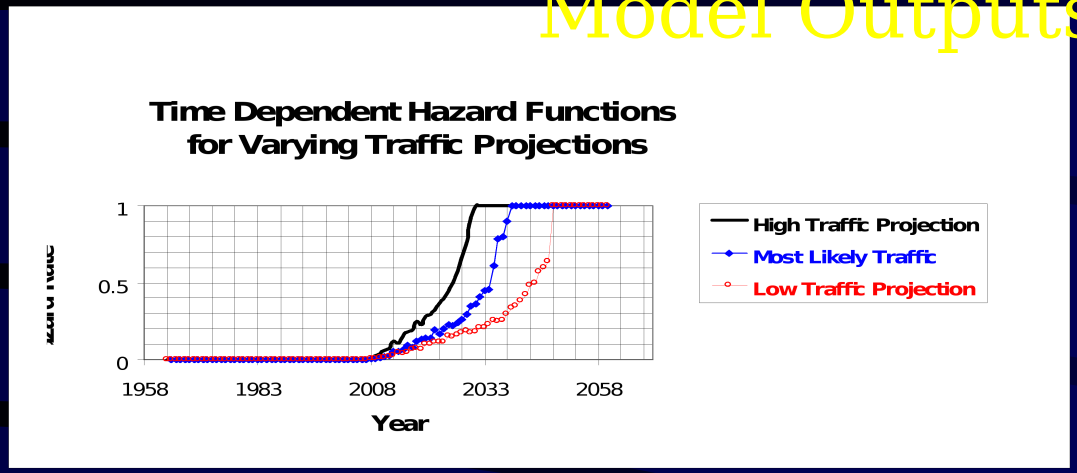
# ORMSS Reliability Integration

## Model Outputs and Integration with Economics




Time dependent probabilities of failure for various alternatives through study period

| Component | | Annual Hazard Rate | Level of Repair | Closure Time | Repair Cost | Effect on Overall Component Reliability |
|---|---|---|---|---|---|---|
| | | Annual Reliability Value (1 - Annual Hazard Rate) | | | | |
| Horizontally-framed Miter Gate | | | New Gate 5% | 365 days in year 1<br>90 days in year 2 | $13,150,000<br>$3,150,000 | Assume R = 1.0 for All Future Years |
| | | Annual Hazard Rate | Major Repair 35% | 45 days in year 1<br>45 days in year 2 | $1,575,000<br>$1,575,000 | Move Back 5 Years |
| | | | Temporary Repair 60%<br>Replace 1st Set of Gates<br>Replace 2nd Set of Gates | 45 days in year 1<br>45 days in year 2<br>30 days in year 3 | $3,575,000<br>$3,575,000<br>$5,050,000 | Assume R = 1.0 for All Future Years |
| SCHEDULED REPLACEMENT BEFORE FAILURE INFORMATION<br>Year 1 -- 30 Days of Closure @ $5,050,00 Year 2 -- 30 Days of Closure @ $5,050,000<br>Future Reliability Will Equal 1.0 Throughout Remainder of Study Period | | | | | | |

Consequence event tree given the limit state is exceeded in the reliability analysis

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# ORMSS Reliability Integration

## Optimized Timing of Component Replacement

- Economic Model (ORNIM)
  - C+ Model Written to Integrate Engineering & Economics
  - Uses Hazard Rates & Event Tree Information
  - Computes Average Annual Costs Associated with Failures
  - Accounts for Component Repair & Navigation Delay Costs
- Different Alternates Tested Consistent with Formulation
  - Fix-As-Fails Baseline Condition
  - Other Maintenance Scenarios (Advance Maintenance)
  - Scheduled Rehabilitations or New Projects

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# *ORMSS Reliability Integration*

## Example of Reliability-Based Economic Evaluation

### MAIN CHAMBER GATE RESULTS FOR OHIO RIVER LOCK

| Scenario | Average Annual Cost | |
|---|---|---|
| Fix-As-Fails | $8,746,700 | |
| Advance Maintenance | $3,728,400 | |
| Replace in 2000 | $1,603,100 | |
| Replace in 2001 | $1,566,500 | |
| Replace in 2002 | $1,531,600 | |
| Replace in 2003 | $1,509,200 | ← OPTIMUM TIME TO REPLACE |
| **Replace in 2004** | **$1,491,800** | |
| Replace in 2005 | $1,494,600 | |
| Replace in 2010 | $2,195,100 | |
| Replace in 2020 | $6,275,100 | |

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# ORMSS Reliability Integration

## Greenup Locks – Main Chamber Miter Gates

- **What Did Original Analysis Predict?**
  - ORMSS hazard rates and economic analysis indicated the optimal time to replace main chamber miter gates by 2004 without a major repair to these gates ahead of that time
  - Analysis was completed in 1999 based upon field performance of similar miter gates on Ohio River system and future traffic trends
- **What Actually Happened?**
  - Routine inspection dewatering of Greenup main chamber in fall 2003 planned for 21 days, no significant deterioration expected
  - Significant damage to gates found that emergency repairs required
  - Closure extended to 54 days (cost to industry and power companies estimated to be in $15 to $25 million range). Thus, gates suffered an “economic” failure.

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# *ORMSS Reliability Integration*

## Deterioration of Ohio River Miter Gates

Cracking Near Quoin Block

Cracking Through Thrust Plate

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# *Plan Development*
## Alternatives

- Maintenance Alternatives
  - Fix major components as they fail
  - Plan for major repairs and fix before they fail
- Operational Alternatives
  - Helper boats, schedule arrivals
  - Congestion fees
- New Construction Alternatives
  - Construct new 1200’ lock
  - Extend auxiliary lock so it is 1200’ long

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# *ORNIM*
# Ohio River Navigation Investment Model

- Identify Optimal Investment Strategies Considering Probabilistic Analysis of Engineering, Economic, and Environmental Features
  - Multiple maintenance scenarios tied to reliability
  - Effectiveness of various repair scenarios
  - New construction versus sustaining existing system
  - Traffic management

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# *ORNIM*

## Analysis Capabilities of ORNIM

- System-wide benefits
- Handles engineering reliability
- Tradeoffs among projects over time
- Tradeoffs between new construction, repairs/maintenance, and traffic management
- Multi-year horizon

# The ORNIM System

Random Closure Probabilities

Reliability Estimates

Repair Plans and Costs

Construction Plans

Lock Risk Module

Cargo Forecasts

Optimal Investment Module

Waterway Supply and Demand Module

Towboat/Barge Operations

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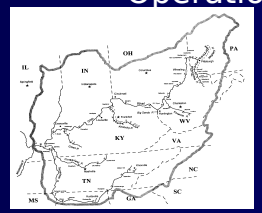
Budget

Optimal Investment in Projects and Maintenance

Lock Operations



River Network

## Optimal Investments for Single Component

**Main Chamber Miter Gate Replacement**

| Scenario | Avg. Annual Cost |
|---|---|
| Current Maintenance | $5,746,700 |
| Aggressive Maintenance | $3,728,400 |
| Replace in 2006 | $1,603,100 |
| Replace in 2007 | $1,566,500 |
| Replace in 2009 | $1,531,600 |
| Replace in 2009 | $1,509,200 |
| **Replace in 2010** | **$1,491,800** |
| Replace in 2011 | $1,494,600 |
| Replace in 2012 | $2,195,100 |
| Replace in 2015 | $5,275,100 |

**OPTIMUM TIME TO REPLACE**

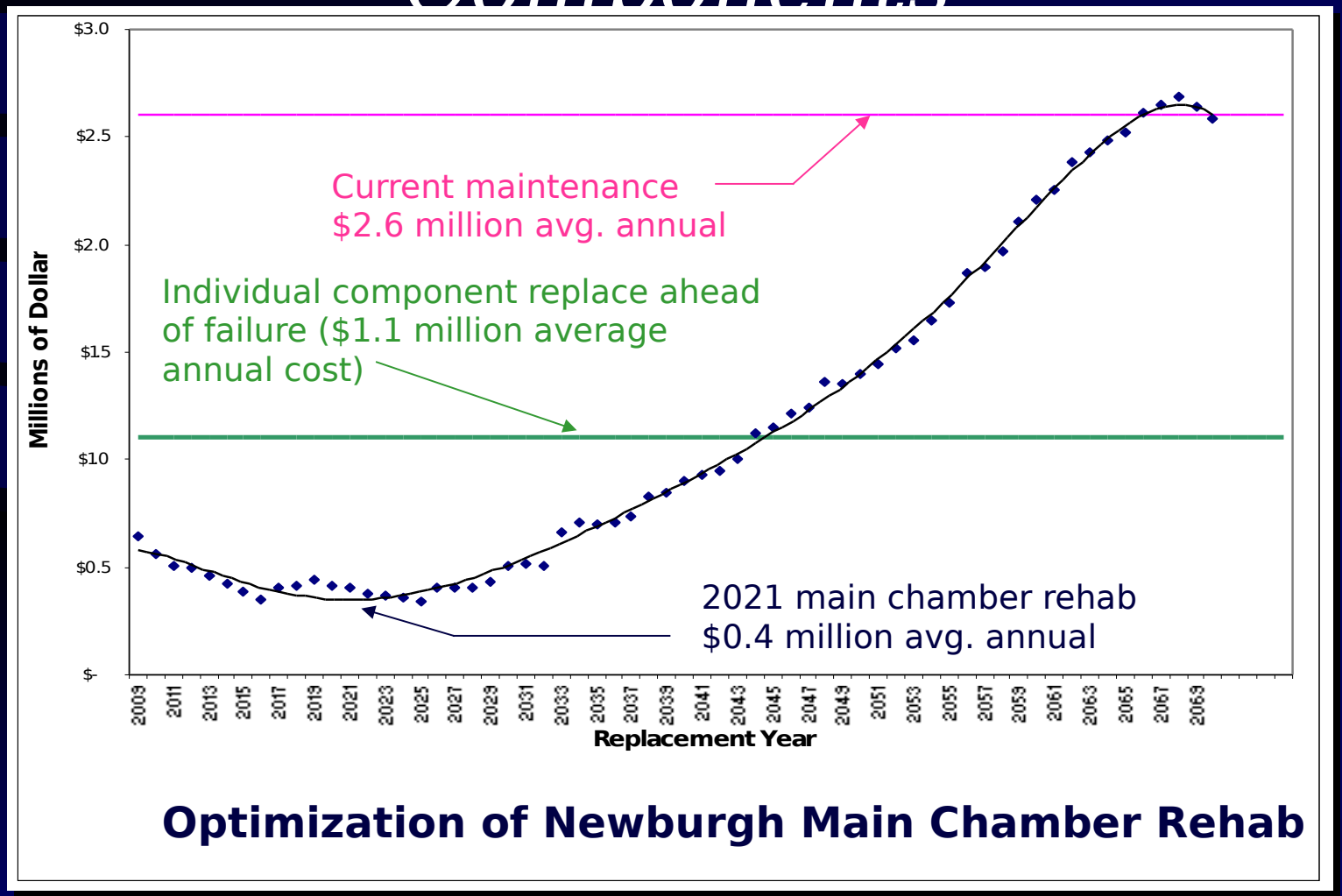
# Optimal Replacement Timing

## All Critical Components for One Lock Chamber

| Feature | Future Traffic 1 | Future Traffic 2 | Future Traffic 3 | Future Traffic 4 |
|---|---|---|---|---|
| Miter Gates | 2010 | 2008 | 2011 | 2014 |
| Culvert Valves | 2014 | 2012 | 2017 | 2019 |
| Miter Gate Machinery | 2020 | 2019 | 2018 | 2020 |
| Hydraulic System | 2018 | 2017 | 2017 | 2018 |
| Electrical Controls | 2015 | 2014 | 2014 | 2015 |

# Optimal Replacement Timing

## Major Rehab vs. Individual Components



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# Other Recent Applications

- Chickamauga Lock Replacement Study (Nashville)
  - Navigation lock on Tennessee River near Chattanooga
  - Mass concrete deterioration due to AAR
  - Reliability models for AAR-effected monoliths, including critical lower miter gate monolith
- Markland Major Rehabilitation (Louisville)
  - High traffic navigation lock on Ohio River
  - Fatigue and fracture of steel miter gates and culvert valves
  - Rehab approved at HQUSACE in FY00. Awaiting CG funds.

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# Studies Spurned from ~~ORMSS~~

- Great Lakes and St. Lawrence Seaway Study
  - Joint effort between USACE, USDOT, and Transport Canada
  - 18 locks, multiple ports, bridges, and tunnels
  - 4 year study evaluating long-term operation of system considering reliability, maintenance, future traffic trends
- Panama Canal Infrastructure Risk and Reliability Study
  - Phase I proposal being reviewed by ACP
  - Multiple year study looking at long-term reliability for various maintenance scenarios, risks associated with seismic events, flood analysis, and potential 3rd lane alternatives
  - Economic aspects include varying rates, traffic trends, etc…

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# THANK YOU

# QUESTIONS ???

David M. Schaaf, P.E.
David.M.Schaaf@LRL02.usace.army.mil
(502) 315-6297